In-Situ Navigation and Timing Services for a Human Mars Landing Site
Part 2: System Design and Simulations

Kar-Ming Cheung*, Charles Lee*, Glenn Lightsey**

***Jet Propulsion Laboratory, California Institute of Technology**

****Georgia Institute of Technology**

SpaceOps 2018, May 28 – June 1, 2018

Marseille, France

Outline

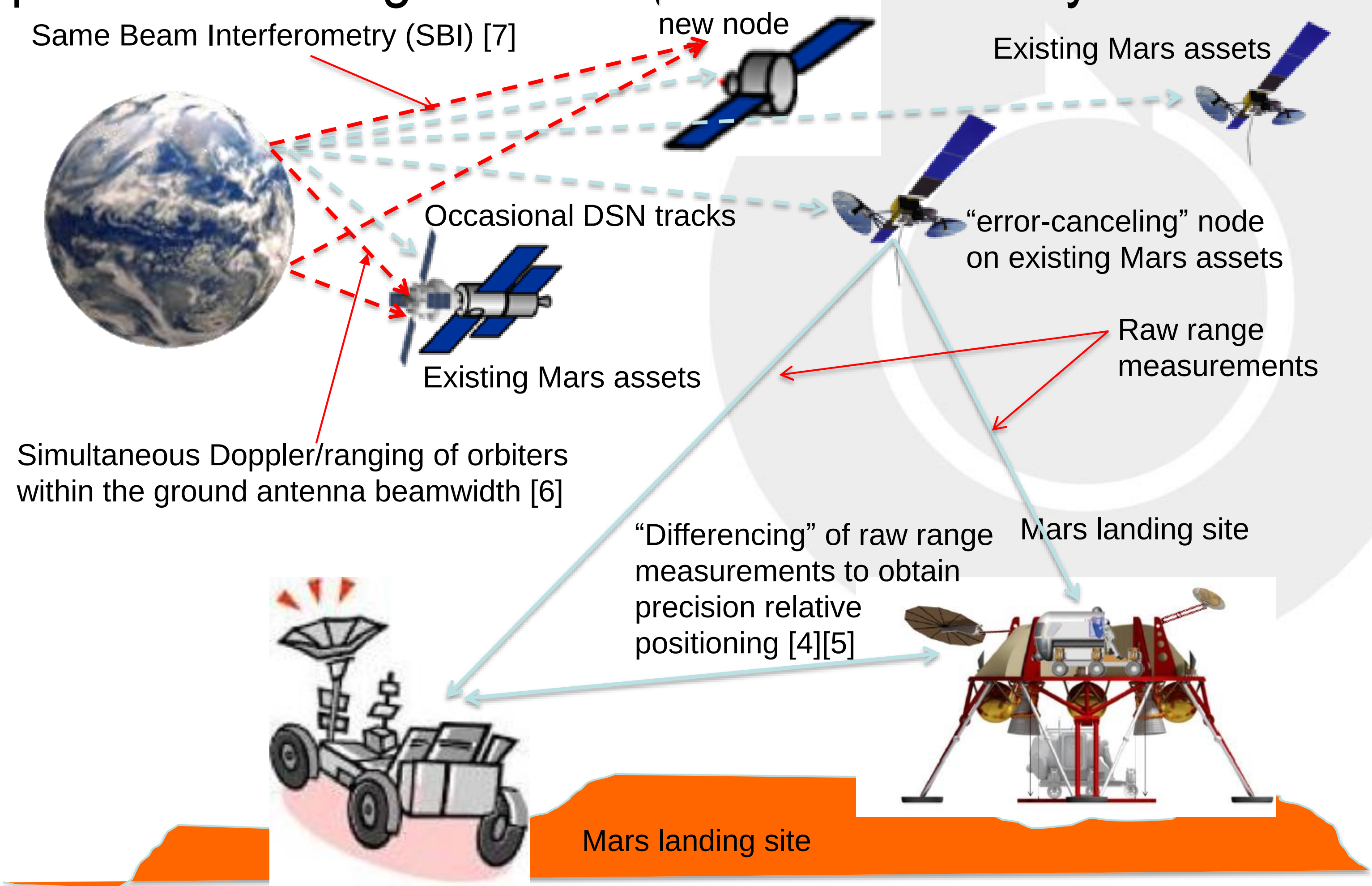
- Background and Summary of Prior Results
- Simulations of Accuracy Performances
- Challenges of Deep Space Tracking of Multiple Spacecraft
- Simultaneous 2-Way Doppler/Ranging
- Same Beam Interferometry
- Concluding Remarks, Ongoing and Future Work

Background and Summary of Prior Results (1)

- We have been working on the system concept of a low-cost low-maintenance Mars Regional Navigation Satellite System (MRNSS) [1] with the following key principles
  - Capitalize on the build-up of orbiting and surface infrastructures on Mars during the human Mars exploration era [2][3][4]
  - Leverage on a new geometric trilateration method that simultaneously performs absolute positioning and relative positioning [5][6]
  - Introduce the concept of using relative positioning that provides regional navigation services in the vicinity of a human Mars landing site (~100 km), thereby relieving the stringent requirements on orbit determination (OD) of Mars navigation satellites

Background and Summary of Prior Results (2)

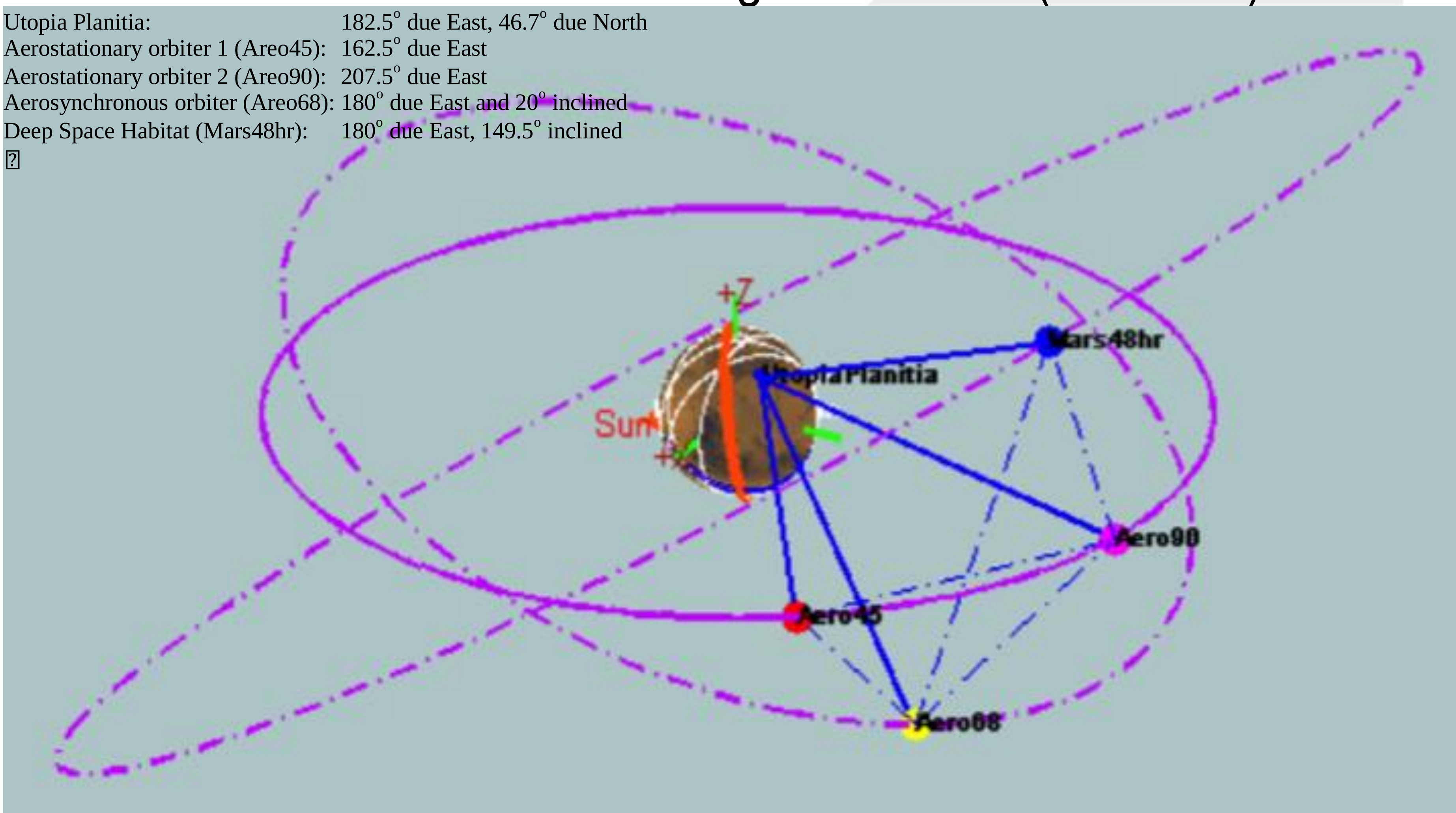
- Proposed Mars Regional Navigation Satellite System



Background and Summary of Prior Results (3)

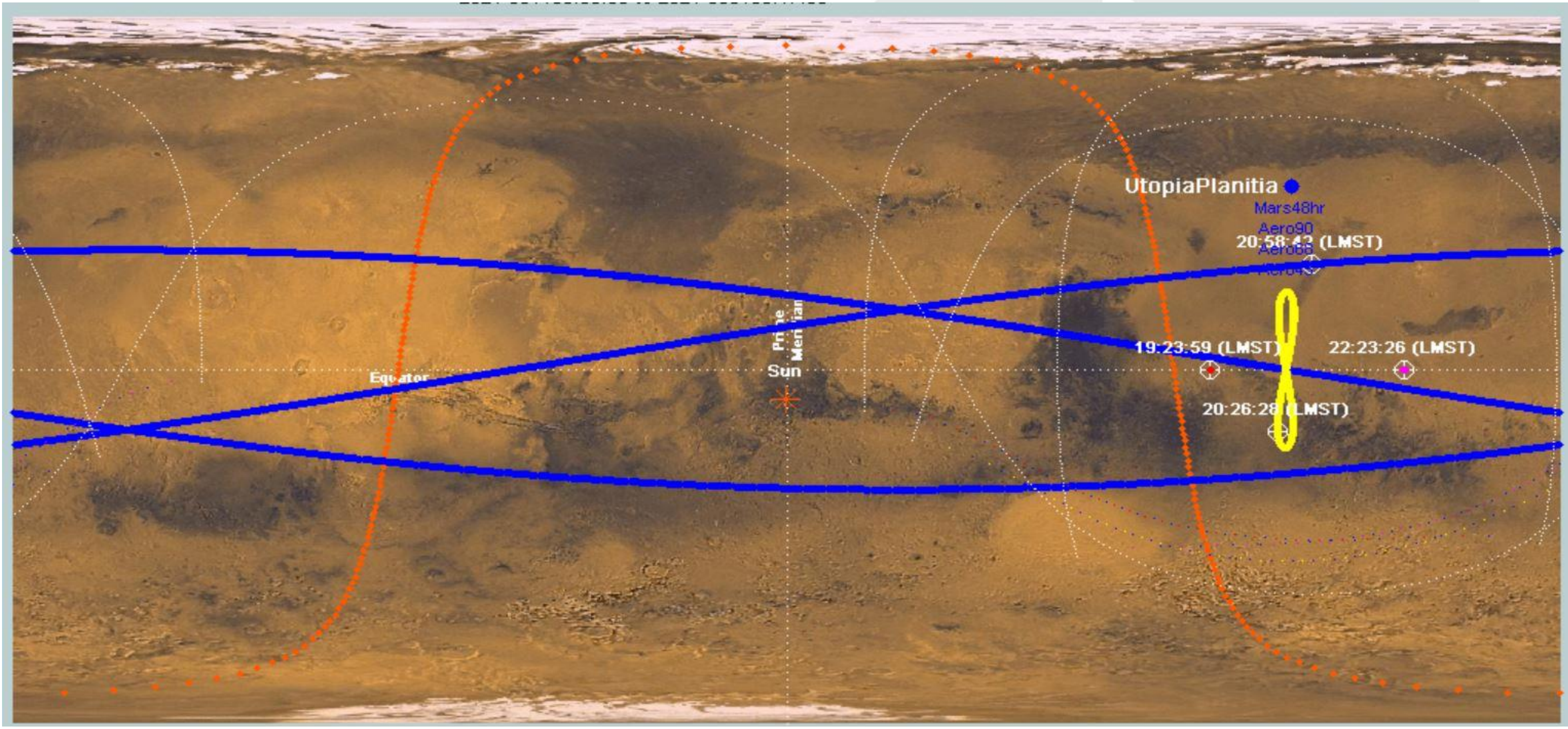
- Orbits of the Notional Mars Navigation Nodes (3-D View)

Utopia Planitia:	182.5° due East, 46.7° due North
Aerostationary orbiter 1 (Areo45):	162.5° due East
Aerostationary orbiter 2 (Areo90):	207.5° due East
Aerosynchronous orbiter (Areo68):	180° due East and 20° inclined
Deep Space Habitat (Mars48hr):	180° due East, 149.5° inclined



Background and Summary of Prior Results (4)

- Projection of the Navigation Nodes on Mars Surface (2-D View)



Simulations of Accuracy Performances

Absolute Positioning

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	0.00	3273.85	6547.69	13095.39	32738.48	65476.99	196431.3	229169.9
	0.10 cm	11.27	3273.70	6547.54	13095.23	32738.32	65476.82	196431.1	229169.7
	0.25 cm	28.19	3273.56	6547.35	13095.01	32738.08	65476.58	196430.9	229169.5
	0.50 cm	56.37	3273.51	6547.12	13094.69	32737.71	65476.19	196430.5	229169.1
	1.00 cm	112.74	3274.15	6547.03	13094.24	32737.04	65475.45	196429.7	229168.3
	2.00 cm	225.48	3278.35	6548.30	13094.06	32735.98	65474.10	196428.1	229166.7
	5.00 cm	563.71	3313.95	6563.76	13099.34	32735.15	65471.23	196423.9	229162.4

Table 1. S_{3D} Absolute Localization Error standard deviation (cm) of the New Scheme. PDOP=113.17.

Relative Positioning

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	14.43	21.57	35.07	65.44	160.06	319.04	956.04	1115.33
	0.10 cm	21.59	26.82	38.47	67.27	160.75	319.32	956.05	1115.32
	0.25 cm	42.77	45.58	53.22	76.58	164.76	321.27	956.58	1115.75
	0.50 cm	81.89	83.33	87.69	103.45	178.67	328.48	958.82	1117.63
	1.00 cm	161.95	162.62	164.84	173.62	226.38	356.41	968.34	1125.72
	2.00 cm	323.00	323.28	324.34	328.78	359.12	452.05	1006.71	1158.71
	5.00 cm	806.95	806.99	807.34	808.99	821.36	865.36	1246.30	1371.59

Table 2. S_{3D} Relative localization Error standard deviation (cm) of the New Scheme.
Distance between reference and target = 100 km. Sigma = 100 m. Delta = 100 m.

Relative Positioning

Our Proposed Scheme		GPS Satellite Position Error							
		0m	0.5m	1m	2m	5m	10m	30m	35m
Pseudo-range error	0 cm	0.14	1.59	3.18	6.35	15.87	31.73	95.20	111.07
	0.10 cm	16.03	16.10	16.32	17.20	22.47	35.45	96.42	112.10
	0.25 cm	40.08	40.10	40.18	40.53	42.99	50.93	103.02	117.79
	0.50 cm	80.15	80.16	80.19	80.36	81.59	85.99	123.99	136.48
	1.00 cm	160.31	160.30	160.32	160.39	160.97	163.19	185.83	194.34
	2.00 cm	320.62	320.61	320.61	320.63	320.89	321.95	333.77	338.52
	5.00 cm	801.54	801.53	801.52	801.52	801.58	801.93	806.47	808.38

Table 3. S_{3D} Relative localization Error standard deviation (cm) of the New Scheme.
Distance between reference and target = 10 km. Sigma = 100 m. Delta = 100 m.

200 – 400 folds improvement in RMSE accuracy

Sigma: media delay
Delta: clock bias

Challenges of Deep Space Tracking for Multiple Spacecraft

- Traditional deep space tracking techniques include Doppler, ranging, and Delta Differential One-Way Ranging (ΔDOR)
- 2-Way Doppler/ranging requires tight coordination between ground and flight (Doppler compensation), and 1 ground station tracking 1 spacecraft (1-to-1)
- ΔDOR is 1-way, but requires 2 ground station tracking 1 spacecraft (2-to-1)
- Tracking requires tying up an antenna for a long time [8]. When number of missions increase, and for missions with multiple spacecraft, there might not be enough DSN antenna assets to meet missions' communications and tracking needs
- There is a desire to extend the current deep space tracking techniques to support multiple spacecraft in a beam to improve the antenna usage efficiency

Simultaneous 2-Way Doppler/Ranging (1)

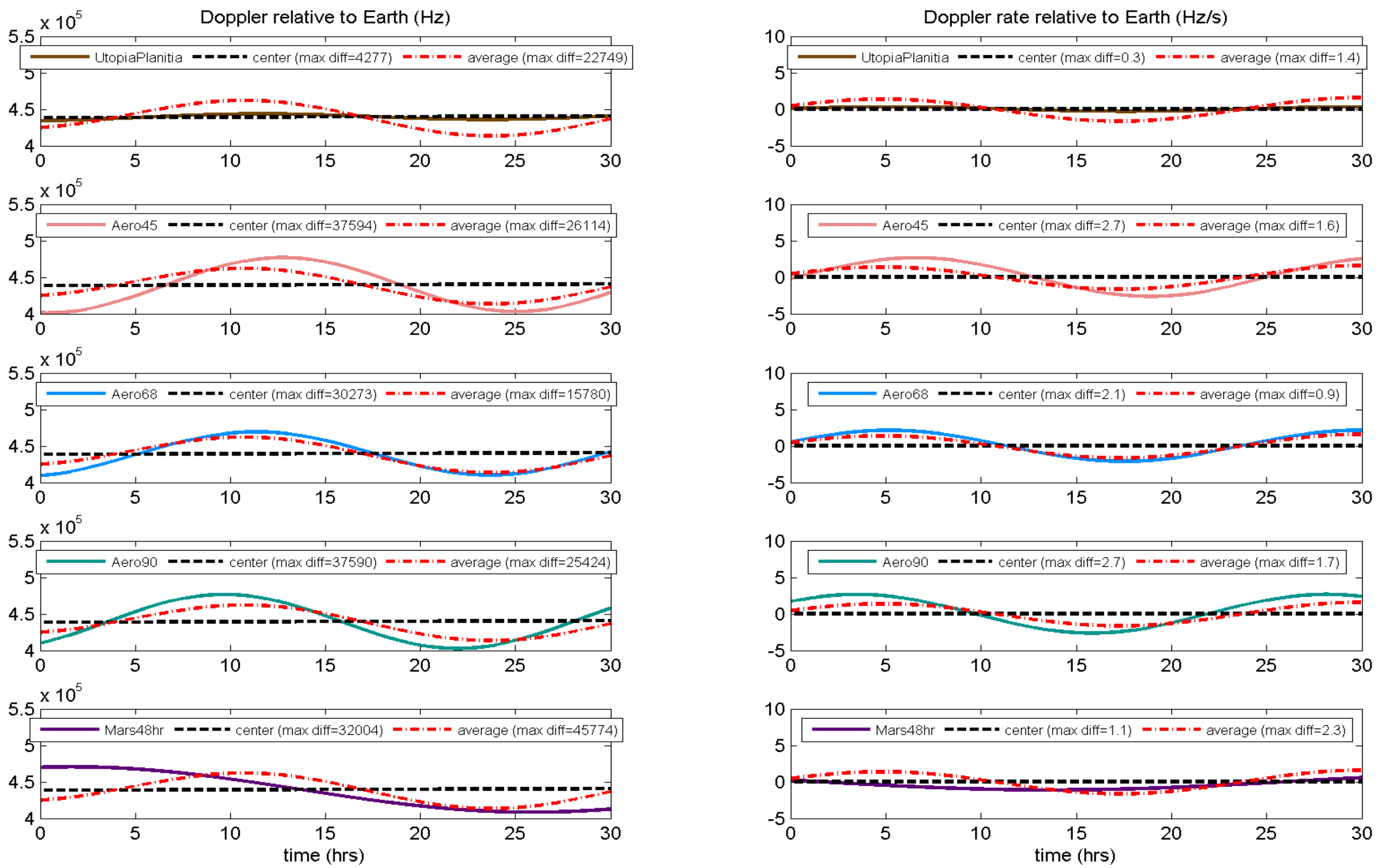
- A collaborative flight-ground architecture
  - Assume Doppler/ranging in X-band, for low rate commands/telemetry
  - All Mars orbiters lie within the beamwidth of a DSN 34-m BWG antenna
  - For N orbiters, the downlink operate in N allocated frequency bands separated by N-1 guide bands to prevent interference
  - Changes in flight and ground systems
    - The N orbiters time-share a single uplink; commands differentiated by SCID
    - The ground “Doppler-compensates” the uplink signal in either ways: a) w.r.t. the Mars center, b) w.r.t. the average (centroid of Doppler of N orbiters)
    - Note: guard bands must be wide enough to accommodate the residual Doppler. Preliminary simulation: residual Doppler and Doppler rate are bounded by 45 KHz & 2.6 Hz/s

Simultaneous 2-Way Doppler/Ranging (2)

- Flight radio upgrade
  - A different turn-around-ratio for each spacecraft so the same uplink would be coherently "turned-around" to modulate the telemetry and ranging signals on a different allocated downlink frequency
  - A well-designed tracking loop that can sweep, acquire, and track the unknown uplink carrier phase and high residual Doppler frequency
- Ground upgrades
  - One ground antenna receives all N downlink signals with different carrier frequencies via Multiple Spacecraft Per Aperture (MSPA)
  - Each signal stream is extracted via band-pass filtering and down-converted to IF for telemetry, Doppler, and range processing

Simultaneous 2-Way Doppler/Ranging (3)

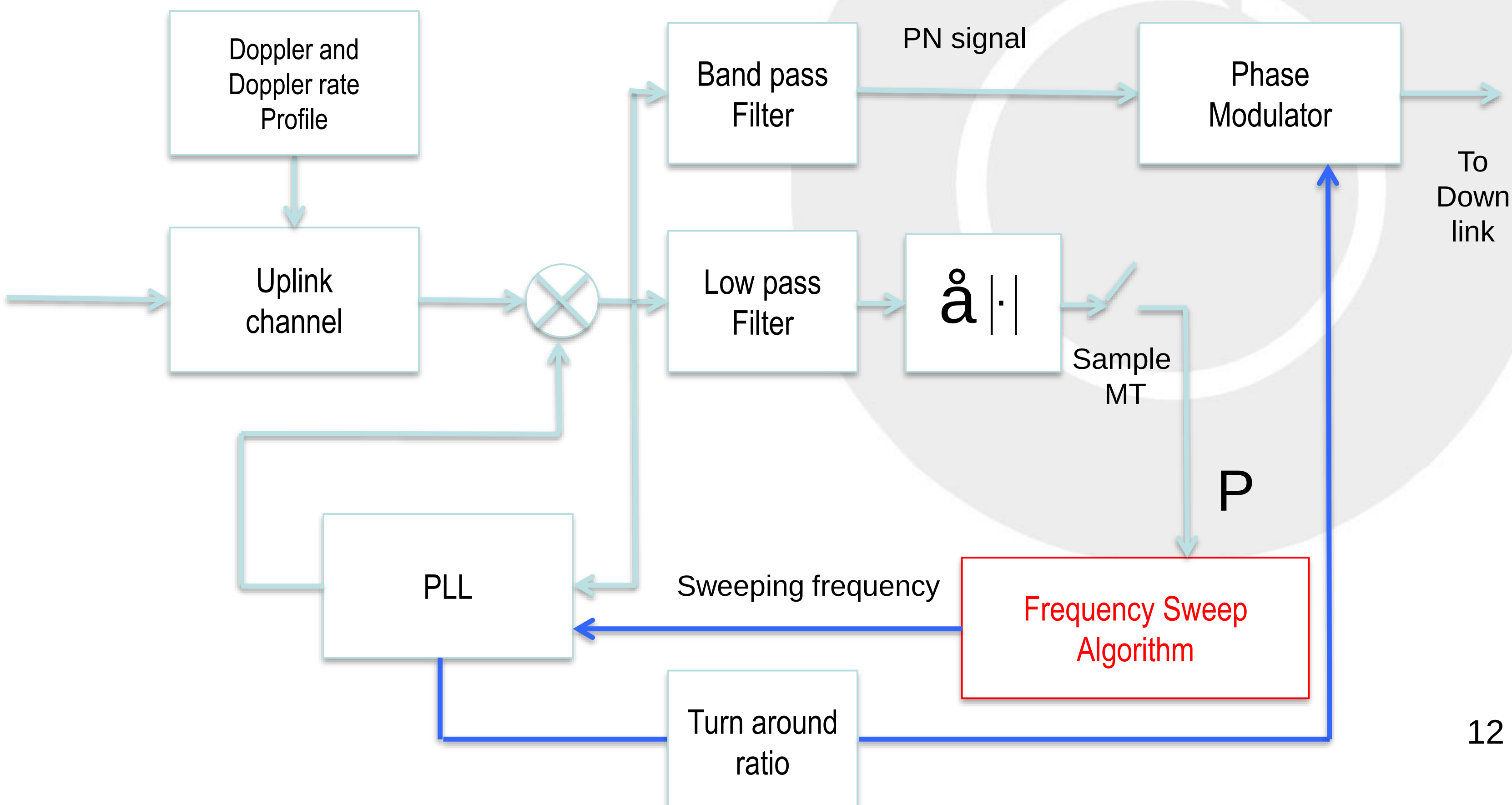
- Doppler and Doppler Rate Profiles



Simultaneous 2-Way Doppler/Ranging (4)

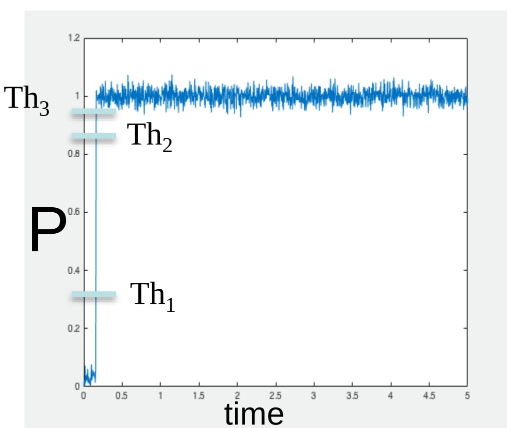
- Spacecraft Radio Schematic

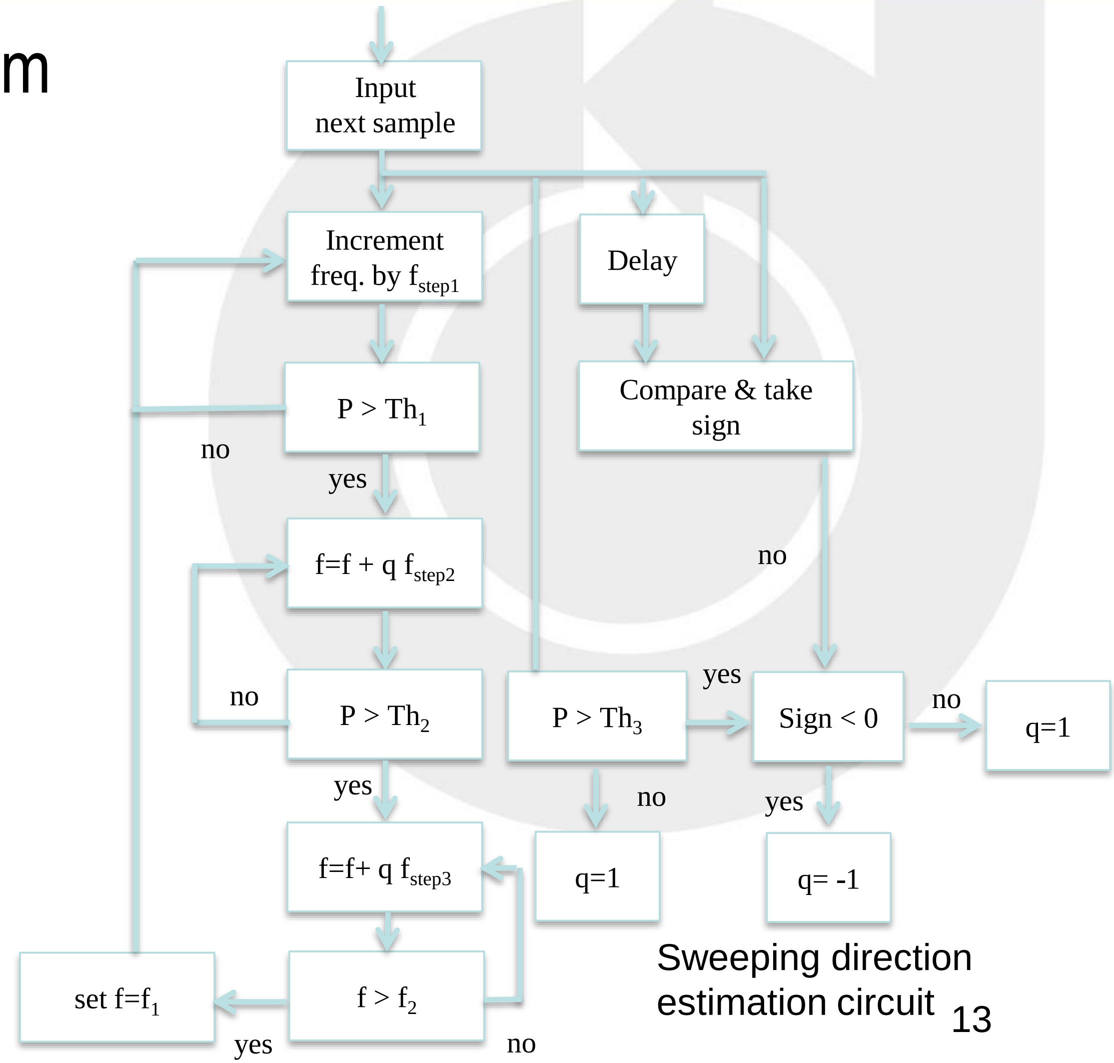
Complex signal representation



Simultaneous 2-Way Doppler/Ranging (5)

- Smart Sweeping Algorithm





Dynamic sweeping circuit

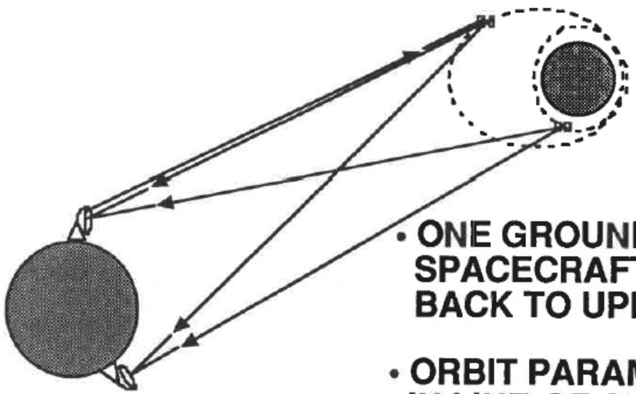
Sweeping direction estimation circuit

Slide provided by Jim Border et. al. “Precise Tracking of the Magellan and Pioneer Venus Orbiters by Same-Beam Interferometry”, AAS/AIAA Spaceflight Mechanics Meeting, Feb 1991, Houston, Texas

Same Beam Interferometry (1)

JPL

PLANETARY ORBITER TRACKING



DOPPLER

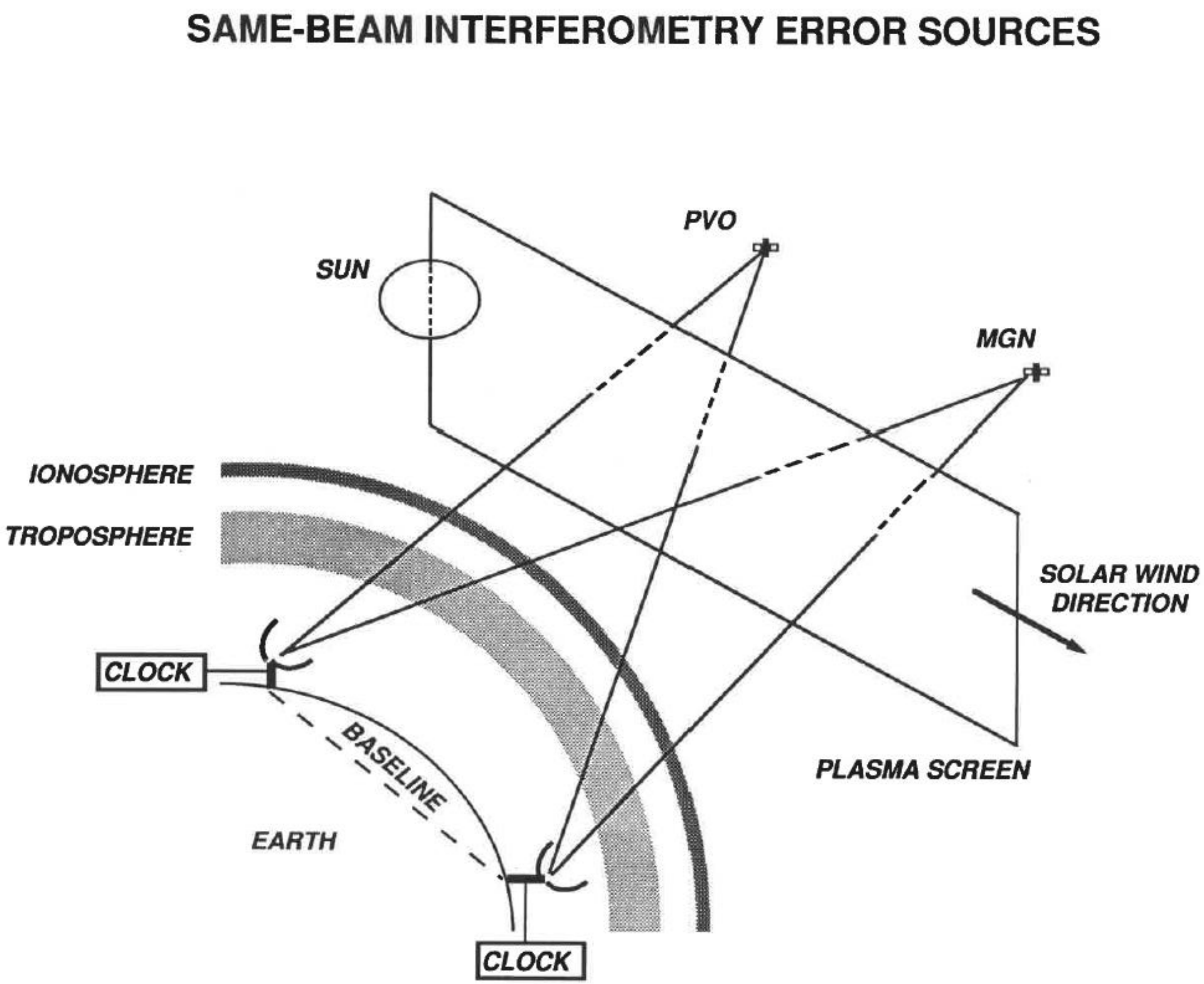
- ONE GROUND STATION *UPLINKS* TO ONE SPACECRAFT, WHICH TRANSPONDS SIGNAL BACK TO UPLINK STATION
- ORBIT PARAMETERS INFERRED FROM SIGNATURE IN LINE-OF-SIGHT DATA

SAME-BEAM INTERFEROMETRY

- TWO GROUND STATIONS *RECEIVE* SIGNALS FROM TWO OR MORE SPACECRAFT
- PLANE-OF-SKY MEASUREMENTS COMPLEMENT DOPPLER

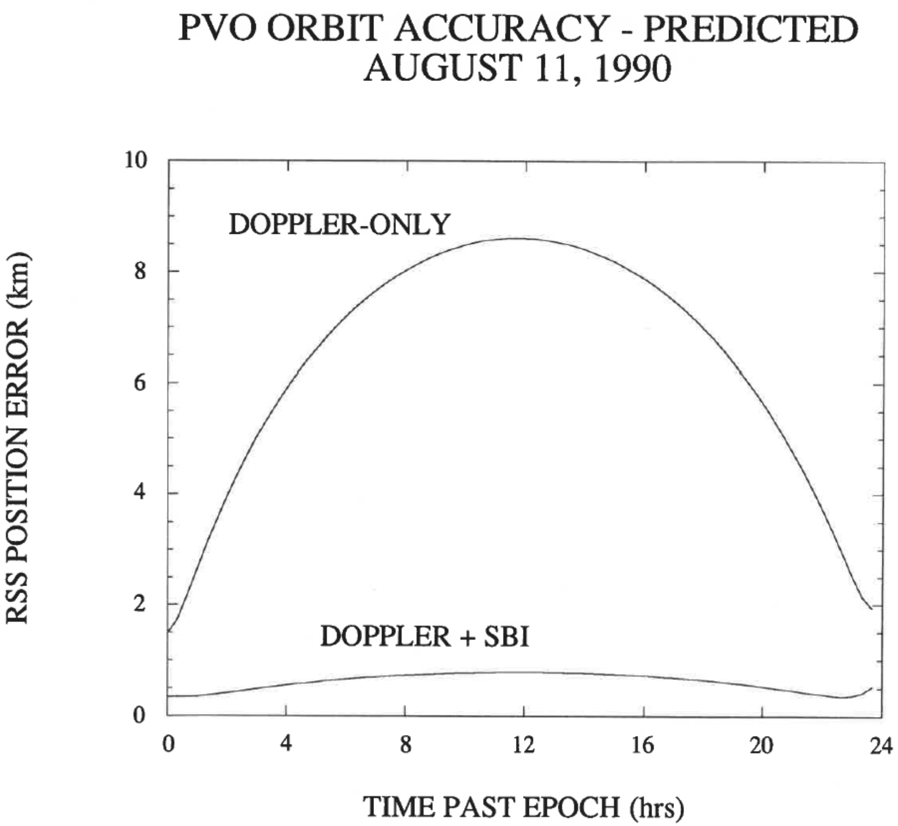
Slide provided by Jim Border et. al. “Precise Tracking of the Magellan and Pioneer Venus Orbiters by Same-Beam Interferometry”, AAS/AIAA Spaceflight Mechanics Meeting, Feb 1991, Houston, Texas

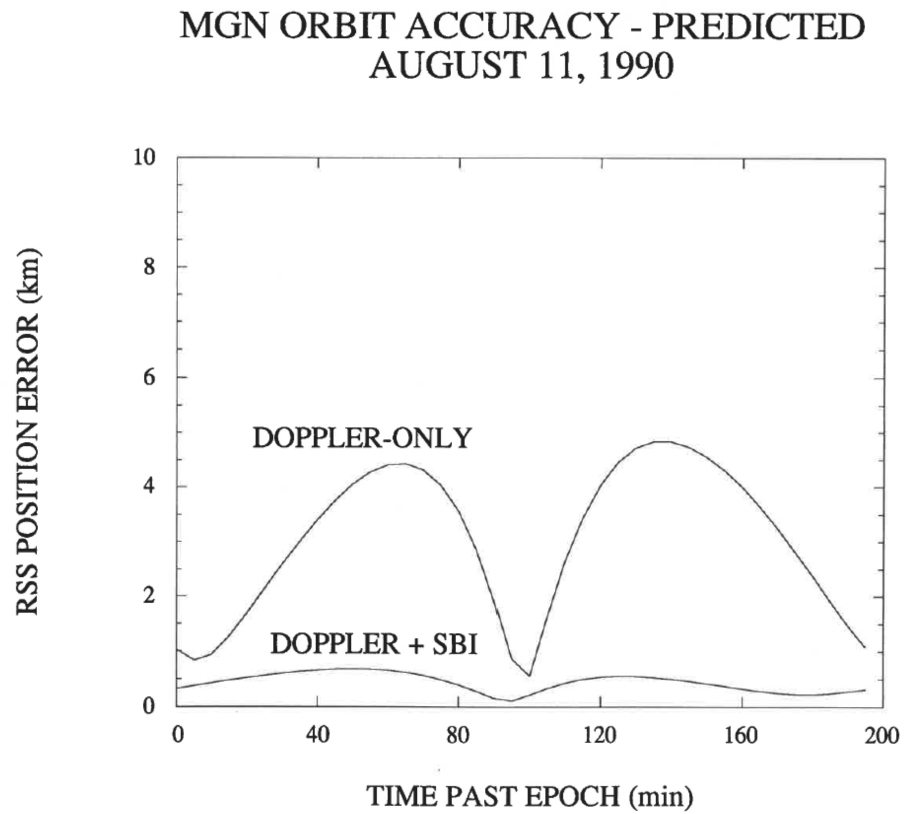
Same Beam Interferometry (2)



Slide provided by Jim Border et. al. “Precise Tracking of the Magellan and Pioneer Venus Orbiters by Same-Beam Interferometry”, AAS/AIAA Spaceflight Mechanics Meeting, Feb 1991, Houston, Texas

Same Beam Interferometry (3)





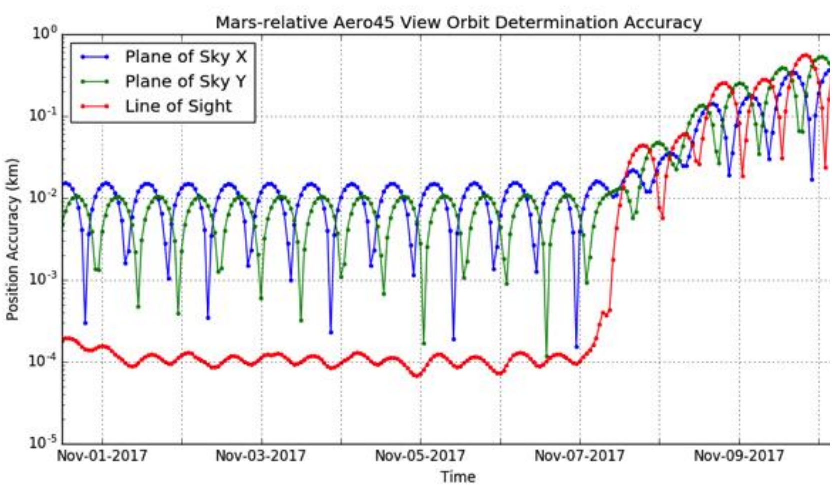
Same Beam Interferometry (4)

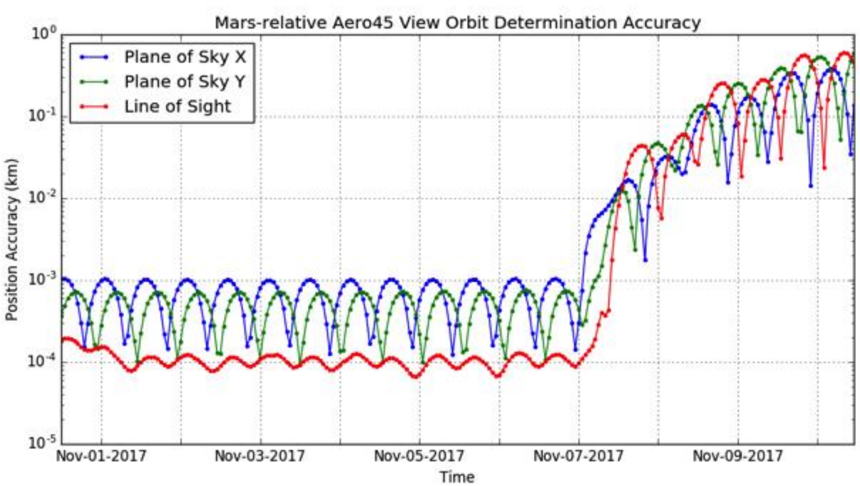
- Since the introduction of SBI, SBI was used or proposed for use in deep space scenarios, e.g. approach/landing, ascent/docking
- Examples

  - Q. Liu, F. Kikuchi, K. Matsumoto, et. al., "Error Analysis of Same-Beam Differential VLBI Technique using two SELENE satellites," Advances in Space Research 40 (2007).
  - M. Chen, Q. Liu, "Study on Differential Phase Delay Closure of Same-Beam VLBI," 2nd International Conference on Computer Engineering and Technology, April 2010, Chengdu, China
  - S. Chen, Q. Liu, "A Study on Accurate Same Beam Interferometry Differential Phase Delay Closure," 12th International Conference on Computer and Information Technology, October 2012, Chengdu, China
  - T. Martin-Mur, D. Highsmith, "Mars Approach Navigation Using the VLBA," Proceedings of the 21st International Symposium on Space Flight Dynamics, Toulouse, France, September 28 – October 2, 2009

Same Beam Interferometry (5)

- Preliminary SBI Navigation Covariance Analysis of Mars Scenario
  - Include spacecraft structure modeling, and media and gravity effects
  - Angular momentum desaturations every day, 1 mm/s uncertainty per axis, 0.1 mm/s also tested
  - Use 3 days of prior data, assume 12-hour latency
  - SBI+2-way Doppler improves OD accuracy (Doppler) by a factor of 2 - 10





Concluding Remarks, Ongoing and Future Work

- We report on the progress on the Mars In-Situ Navigation Study
  - Position accuracy simulations confirm the feasibility
  - Introduce simultaneous tracking techniques to improve OD accuracy
- Establish analysis/simulation processes and tools for more Mars scenarios, and can be easily extended to lunar scenarios
- Ongoing and future work
  - Design of navigation signaling scheme that enable fast integer-ambiguity-resolution for carrier phase tracking in the Mars poor PDOP environment
  - Examine the effect of dual & triple frequency receivers to improve the acquisition and tracking performance at Mars
  - Conduct hardware-in-the-loop demonstration

References

- [1] K.Cheung, C. Lee, "In-Situ Navigation and Timing Services for a Human Mars Landing Site Part 1: System Concept," September 2017, 68th International Astronautical Congress, Adelaide, Australia.
- [2] H. Price, J. Baker, F. Naderi, A Scenario for a Human Mission to Mars Orbit in the 2030s: Thoughts Toward an Executable Program – Fitting Together Puzzle Pieces & Building Blocks, Jet Propulsion Laboratory, California Institute of Technology. Presented at the Future In-Space Operations (FISO) Telecon, May, 2015.
- [3] Mars Architecture Steering Group, Human Exploration of Mars Design Reference Architecture 5.0, Technical Report, NASA, 2009.
- [4] D. Bell, R. Cesarone, T. Ely, C. Edwards, S. Townes, MarsNet: A Mars Orbiting Communications & Navigation Satellite Constellation, IEEE Aerospace Conference 2000, March 2000, Big Sky, Montana.
- [5] K.Cheung, C. Lee, A Trilateration Scheme for Relative Positioning, IEEE Aerospace Conference 2017, Big Sky, Montana, March 2017.
- [6] K. Cheung, C. Lee, A Trilateration Scheme for GPS-Style Localization, Interplanetary Network Progress Report, 42-209, May 15, 2017.
- [7] J. Border, W. Folkner, R. Kahn, and K. Zukor, "Precise Tracking of the Megellan and Pioneer Venus Orbiters by Same-Beam Interferometry, Part I: Data Accuracy Analysis," Interplanetary Network Progress Report, 42-110, August 15, 1992.
- [8] P. Romero, B. Pablos, G. Barderas, "Analysis of Orbit Determination from Earth-Based Tracking for Relay Satellites in a Perturbed Areostationary Orbit," Acta Astronautica 136 (2017) 434-442, April 4, 2017.

Shaping the Future of Aerospace